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A Study of the Fish Capture Process in a Bottom Trawl by Direct Observations from a Towed Underwater Vehicle

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A Study of the Fish Capture Process in a Bottom Trawl by Direct Observations from a Towed Underwater Vehicle

J Main and G I Sangster

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Introduction

It has long been clear that fish are not passively sieved out of the sea by trawls and seine-nets. The interrelationship between fishing gear performance and fish behaviour is complex, and it is important to isolate those features of fish behaviour and fishing gears which determine the efficiency of the capture process. A high priority has been given to studies of the reaction of fish to the individual components of a fishing gear and the various stimuli generated by each component so that we can determine to what effect vision, hearing and other senses are used by the fish. However, we must not forget that the desired end result of applied fish behaviour studies is a complete and accurate knowledge of the over-all process, including all stimuli and how they affect the fish. Numerous attempts have been made to tackle these problems by attaching instruments to the fishing gear, for example, remote cameras (Craig and Priestley, 1963; Beamish, 1967; Parrish, Blaxter, Pope and Osborne, 1967), remote television (Sand, 1957; Livingstone, 1959). These techniques supplied information on fish behaviour in close proximity to the net in the field of view of the camera. Indirect observation techniques such as echosounders (Okonski, 1967; Scharfe, 1963; Chapman and Hawkins, 1967), sector scanner (Harden-Jones, 1967; Hemmings, 1974) and sonar (Mhor, 1960, 1967) have been used to investigate the herding behaviour of the fish in response to the visual and acoustic stimuli produced by moving seine-net ropes and trawl bridles. Our greatest advance in the knowledge of how fish are caught has come from direct observations of Danish seines by diving scientists (Parrish, Hemmings, Chapman, Main and Lythgoe, 1964; Hemmings, 1967, 1973; Sangster and Hemmings, 1971). More recent developments by the present authors resulted in a safe, free-swimming technique which has enabled divers to hang on to towed pelagic and demersal trawls and make direct measurements of the gear geometry with some limited observations of the fish in these gears (Main and Sangster, 1976). There are great advantages in direct observation of fish behaviour, but at towing speeds in excess of 1.5m s^{-1} (3 knots) the drag due to the water flow against the diver is too great to allow long-term observations (High, 1967; Main and Sangster, 1978a). These problems were overcome by the development of a towed underwater vehicle, TUV II (Plate I), carrying a pilot and observer wearing conventional SCUBA gear. The TUV II provides shelter for the diving scientists, allowing periods of direct observation limited only by the necessity to avoid decompressing in the sea (Main and Sangster, 1978b). Using TUV II and operating a hand-held underwater television camera, we successfully recorded on video tape the action of various types of trawls and other towed gears (Main and Sangster, 1979, 1981). This paper describes the behaviour of several commercially important species of fish observed in, and reacting to, a bottom trawl, using still and television cameras from TUV II. Future developments in fish capture research are discussed.

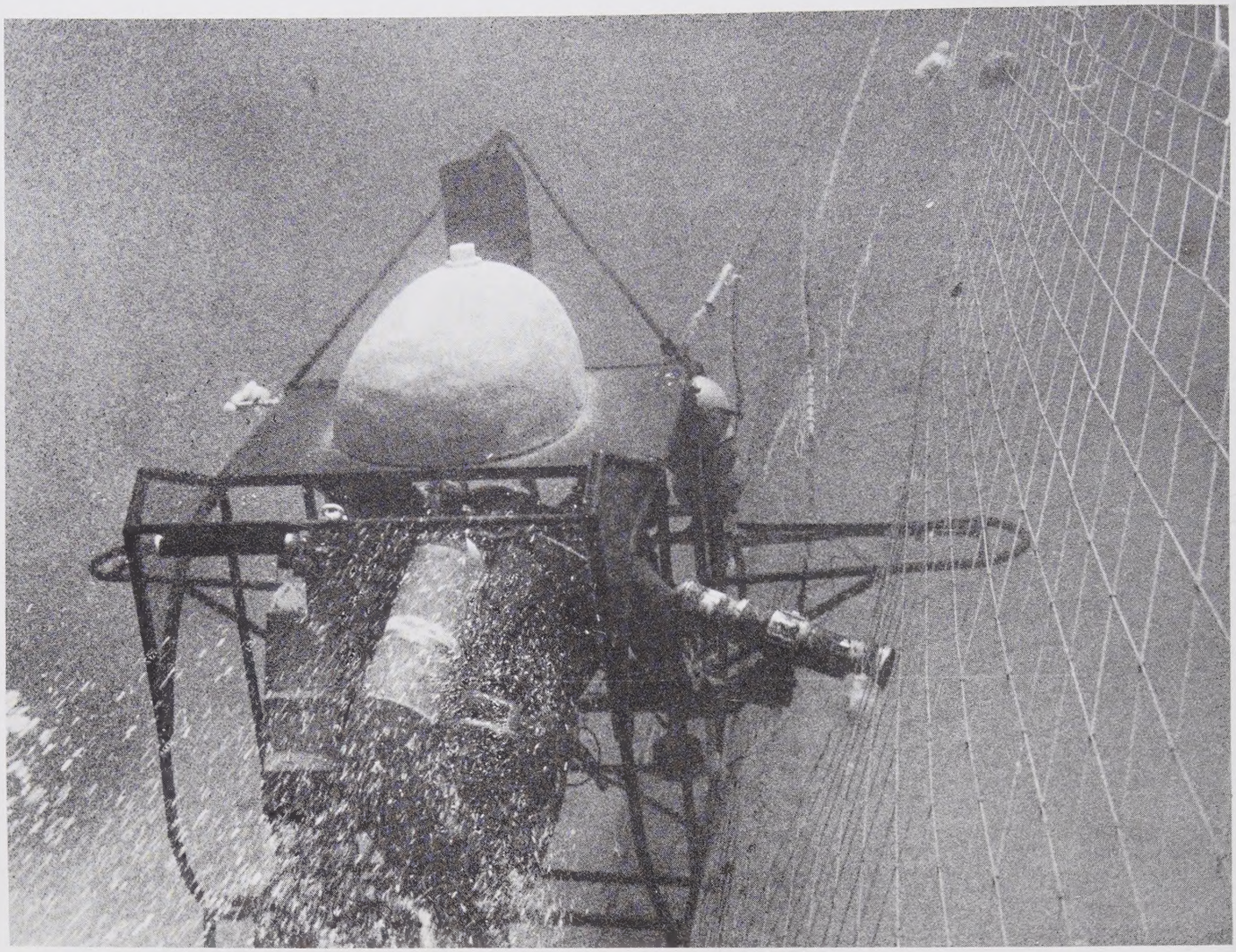
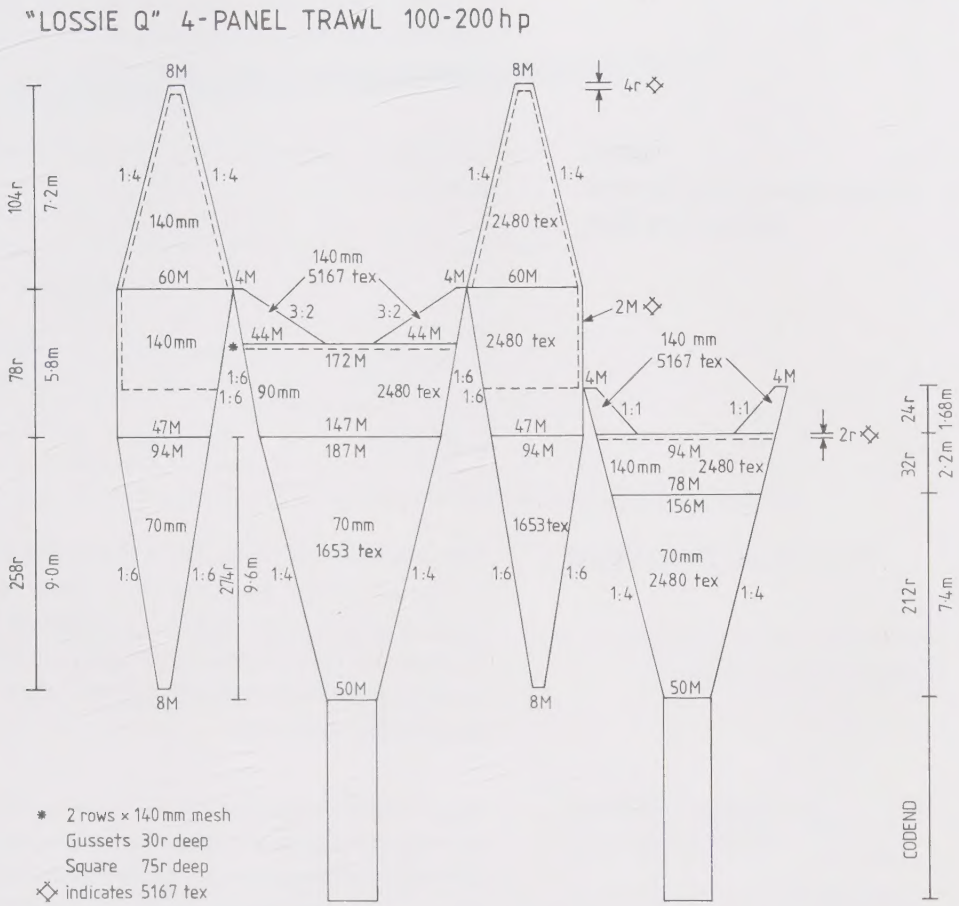


Plate I. The Towed Underwater Vehicle (TUV II) on the port side of the trawl.

Materials and Methods

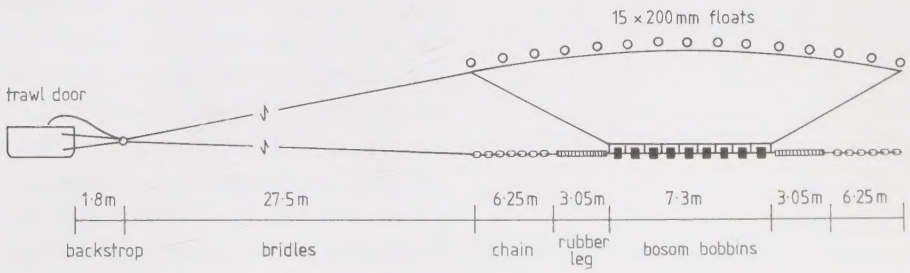
Experiments were conducted during 1980 on fishing grounds off Gairloch, Wester Ross, Scotland, using the fisheries research vessel "Mara" (200hp, 22m) arranged as a side trawler and also as the towing vessel for TUV II. The depth was from 40m, shallowing gently to 34m, followed by a steep rise to a flat area in 20m. This ground allowed a 45 minute tow at 1.5m s^{-1} (3 knots). Towing speed was monitored using speed logs on board the towing vessel and on the TUV II. The net used was a "Lossie Q" bottom trawl, a version of the Aberdeen 4-panel trawl series described by Corrigall and Watson (1977). The trawl was rigged with a bobbin ground gear and its performance on both smooth sand and rough ground was described by Main and Sangster (1979). The trawl boards were steel type rectangular Vee (1.7m)x 1.0m). The net and its rigging specification are described in Figure 1. Trawl board spread, wing end spread and headline height were measured using a diver-held sonar unit. This method of obtaining gear dimensions *in situ* is described in detail by Main and Sangster (1981). "Mara" towed the fishing gear and manoeuvred into position for the proposed tow, so that the diver controlling the TUV II had time to submerge and be in the correct position alongside the gear in a depth of water which would permit an acceptable duration of continuous filming of fish

behaviour in the vicinity of the net, carefully calculating the diving time to avoid decompressing in the sea. The television pictures were obtained using a hand-held underwater camera fitted with a RCA Sitcon tube. A clock inserted on the video frames allowed real time data to be synchronised with the television picture. Thus the behaviour patterns of fish as they reacted to the fishing gear could be studied and analysed at length after the completion of each haul.



HEADLINE – 22·1m (6·55 + 3·65 + 1·70 + 3·65 + 6·55)
GROUNDROPE – 13·4m (3·05 + 7·3 + 3·05)
FISHING LINES – 14·3m (3·2 + 2·2 + 3·5 + 2·2 + 3·2)
WINGLINES – 6·5m
GROUNDCHAINS – 6·25m

Rigging Specification



BOSOM – 380 mm rubber wheel bobbins RUBBER LEG – 90mm rubber disc All on 12 mm drag alloy chain

Figure 1. Net diagram and rigging specifications of the Aberdeen 4-panel "Lossie Q" trawl used in the experiments.

Still photographs were obtained using a Nikonos III underwater camera fitted with a 15mm lens. Kodak Tri–X 35mm negative film uprated to 800 ASA was used and processed with "Promicrol" developer. Only natural light was used throughout the experiments. From both the video cassette tape and still shot prints we were able to build up a comprehensive picture to demonstrate the fish behaviour in relation to the trawl. Water flow measurements inside the net were recorded using a diver-held digital flow-meter (General Oceanics Inc., Florida, USA). Small holes were cut in the panels of the net, in the areas relevant to the fish capture process. Readings from the flowmeter were transmitted to the surface or recorded on a cassette tape recorder carried by the diver. These techniques were described in detail by Main and Sangster (1978a, 1981).

Results

Measurements and Observations of the Gear

The linear measurements of the gear using the hand-held sonar unit are given in Table I.

Table I

Fishing gear dimensions

Trawl Board Spread	Wing End Spread	Headline Height	Wing End Height	Bridle Angle
20 metres	8.5 metres	4 metres	2.1 metres	11.5°

Trawl Board Sand Cloud

The sand clouds from the rectangular Vee boards were found to be similar in size and shape to those from the Vee board experiments described by Main and Sangster (1981). The clouds passed just outside the wings of the "Lossie Q" trawl rigged with 27.5m (15 fm) bridles. At no time during these experiments were the inner edges of the sand clouds more than 1m outside the wing tips.

Ground gear Contact with the Sea Bed

The design of the "Lossie Q" – 4-panel trawl net keeps the belly and quarters slightly raised immediately behind the bobbin rig even on hard grounds. Video recordings showed that the ground gear appeared to be slightly light at the quarters, thus permitting the escape of some species of fish. However, the success of this gear is probably due to the ease with which the net lifts in parallel with the ground gear over rough ground (Main and Sangster, 1979).

The trawl was filmed towing from a flat plateau down a 10° slope, as shown in the echosounder trace in Plate II. The video recording showed the ground gear to be in good contact with the sea bed on the flat ground, but to leave the bottom when towing over the rim and down the slope. The whole gear, from boards to net, was in midwater for a period of time. The divers did not observe the gear returning to the sea bed. The fish which had been herded into the path of the net escaped under the bobbin rig immediately the gear left the ground. Towing in the opposite direction up the slope gave similar results. In this case, the otterboard spread and headline height decreased as the bridles passed over the rim and were pulled down, and eventually the ground gear lifted off the bottom. On the flat ground at the top of the slope, the gear quickly returned to its normal towing shape. Figure 2 illustrates these points.

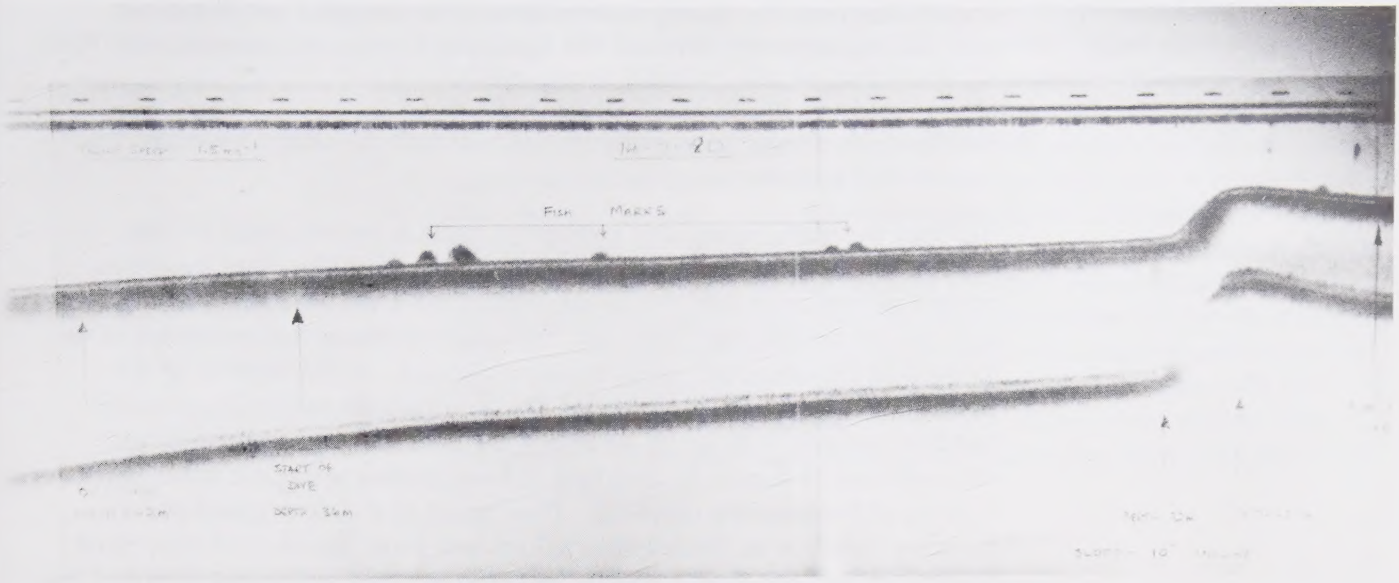


Plate II. Echosounder trace of the fishing grounds off Longa Island, Gairloch.

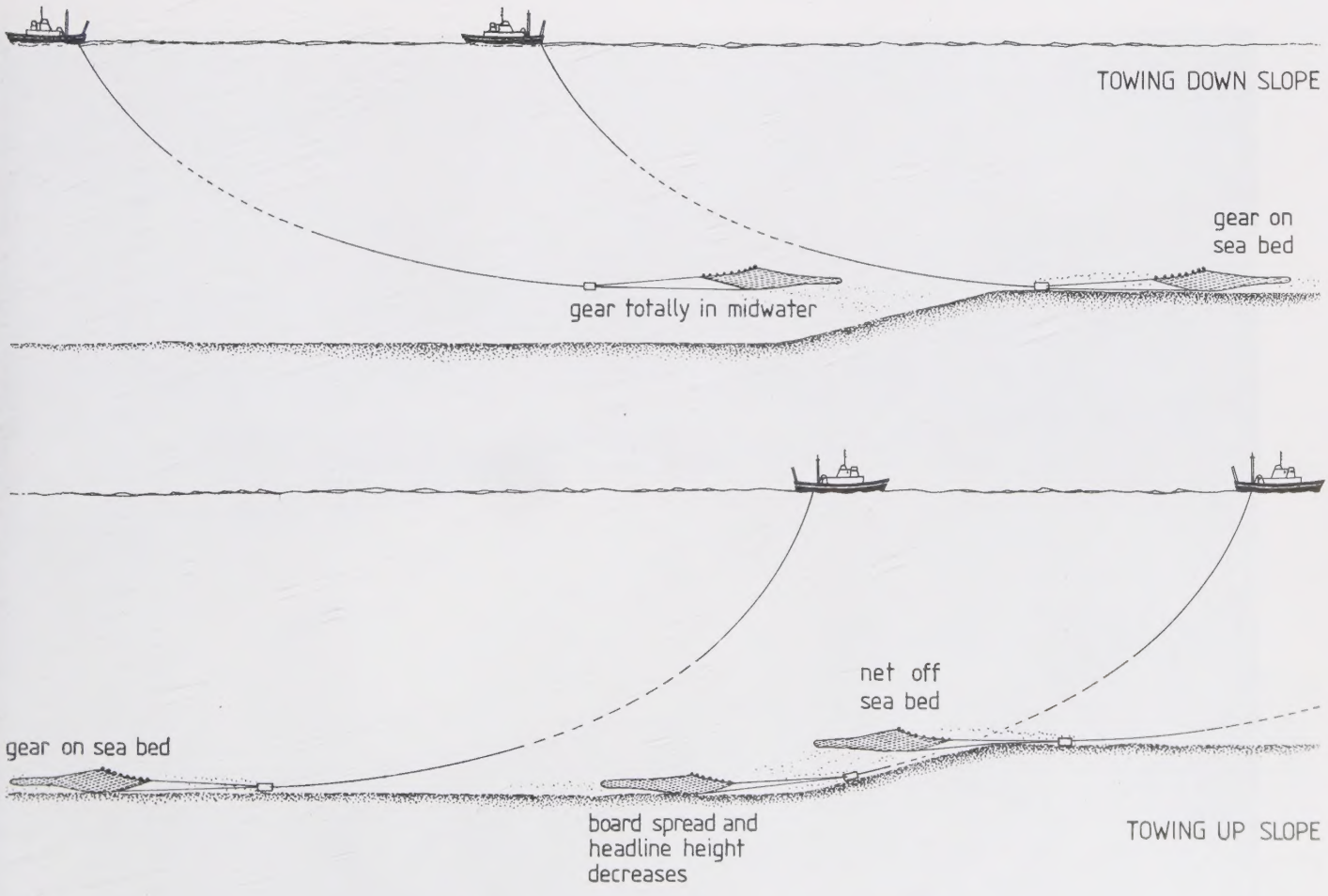

TOWING DOWN SLOPE
gear on sea bed
gear totally in midwater
net off sea bed
gear on sea bed
board spread and headline height decreases
TOWING UP SLOPE

Figure 2. Sketch of the behaviour of the "Lossie Q" 4–panel bottom trawl towing in both directions over the sloping fishing area.

Underwater visibility during these experiments was good and the divers were able to identify individual fish species at a range of approximately 10m.

Haddock, *Melanogrammus aeglefinus* (L)., length 20—38cm measured from the cod-end sample.

Haddock generally swam with steady tail beats in the direction of tow, equidistant between the wings and bridles. The formation was a narrow column or ribbon of fish, five or six individuals wide, swimming no higher than 1m off the sea bed (Plate III). This narrow line of fish extended as far forward as the observers' range of vision allowed. In the vicinity of the bosom bobbin groundline, however, the accumulated swimming group of haddock was still only up to 1m above the bottom but was more spread out, as shown in Figure 3. Haddock did not display any panic behaviour in front of the bosom groundline. They swam at the same speed and in the same direction as the net with a 'kick and glide' action until they tired or lost interest, and then gradually lost ground. The typical behaviour of the tiring haddock falling back was for the fish to lift head up, swim slowly upwards and turn while rising from the sea bed. Haddock rose immediately in front of the bosom groundline and as far as 5m ahead of the gear before they turned back towards the net. Haddock that rose as far as 5m ahead of the bosom were seen on occasions to rise over the headline and escape. Small haddock escaped through the top netting panels but the larger ones attempting to escape were meshed (70mm mesh). Figure 4 demonstrates the typical behaviour of the tiring haddock. No haddock escaped under the ground gear, and only a few single fish escaped under the flying wing

Plate III. Haddock in line formation between the wings of the "Lossie Q" 4—panel trawl. Towing speed 1.5m s^{-1}.

line and swam along the corridor between the net and the sand cloud. Analysis of the video tapes showed that the larger haddock swam in front of the gear at 1.5m s^{-1} for no more than 2½ minutes before dropping into the net, whilst the smaller fish swam here for periods of only 30 to 60 seconds. In the batings or funnel of the net all haddock turned and orientated themselves to swim forwards with the net again, but at a speed slower than that of the gear. They slowly lost ground and dropped back down the funnel of the net. In the batings, where the diameter of the funnel reduces to approximately 1m, haddock became agitated. Many escaped by striking against and wriggling through the sides and top panels. The mesh size (Fig. 1) in this area of net was 70mm and the video tapes showed that the shape of the meshes in the top panel were very nearly square. No fish attempted to escape through the lower panel at this point as sand from the bobbin ground gear was billowing back along the lower sections of the net (Plate IV).

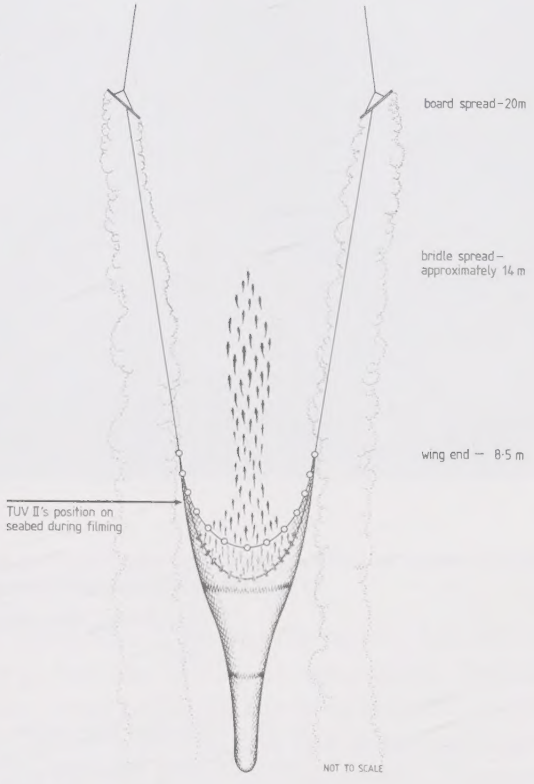


Figure 3. Plan view, showing the typical narrow column formation of haddock swimming equidistant between the bridles and wings of the gear. The formation is more spread out in the vicinity of the bosom bobbin groundline.

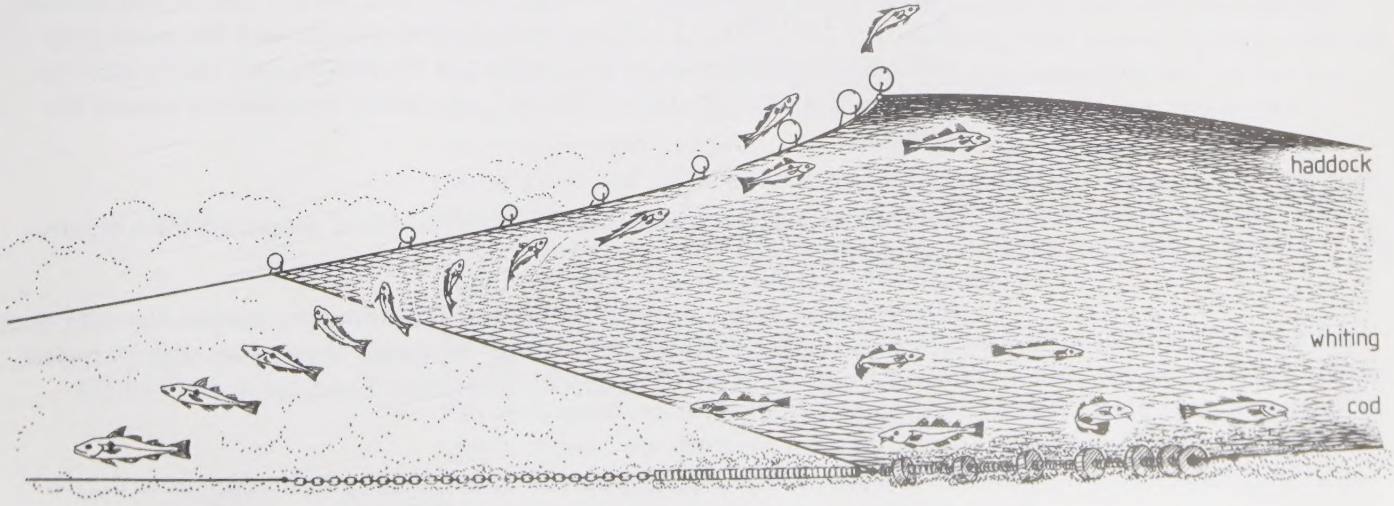


Figure 4. The typical behaviour of the tiring haddock, whiting and cod as they fall back into the net.

Plate IV. Haddock swimming inside the funnel of the net, close to the top netting panel. Sand from the ground gear was billowing back through the lower parts of the net.

In the cod-end fish were frequently seen to be forced against the meshes and then thrown forward owing to water turbulence and caught up in a swirling water mass (Plate V). Small haddock (length 20–25cm) escaped through the cod-end meshes and were seen to swim away with no apparent damage.

At a towing speed of 1.5m s^{-1}, the water flow readings inside the partially fish-filled cod-end (Plate V) ranged from 0 to 0.3m s^{-1} and on the outside from 0.7 to 0.85m s^{-1}. Immediately behind the cod-end the water mass was sucked along in the same direction as the moving gear giving readings up to a maximum of minus 0.6m s^{-1}, at a point immediately behind the codline.

Whiting, *Merlangius merlangus* (L.), size 23–42cm, measured from the cod-end sample.

Whiting were seen clear of both bridles, swimming in a similar line formation with the haddock between the wings. However, they swam slightly higher off the sea bed than the haddock, ie between 1 and 2m in front of the bobbins.

In the area of the bosom groundline, the whiting formation, as with the haddock, was similarly spread out laterally, and fish were seen extending from quarter to quarter. A regular tail beat swimming behaviour pattern

Plate V. Fish in the cod-end being tossed around due to water turbulence.

was apparent for those fish in the line formation, but changed to a "kick and glide" action in fish near the bosom groundline. Occasional agitated swimming was seen when collisions occurred between individuals. In these instances whiting darted both sideways and ahead, and seemed to be searching for vacant space for free swimming movement. The largest whiting when arriving immediately in front of the ground gear were not observed to swim for more than 1 minute at a towing speed of 1.5m s^{-1} and the smaller ones dropped back into the net after approximately 30 seconds. Whiting generally swam in the direction of tow, at a speed slightly slower than that of the net. This meant that single fish slowly dropped back towards the bosom groundline where, unlike the haddock, they turned through 180° in the horizontal plane and swam slowly into the advancing net. A few individuals rose up from the sea bed but these may have been influenced to swim upwards by following the rising haddock. In the batings, fatigued whiting still had sufficient energy to turn and swim forwards again with the net where the cross-sectional diameter was reduced to approximately 2m. These fish then slowly dropped back to a position just before the join of the extension panel and the cod-end (1m diameter).

Most whiting at this point swam close to the top netting as sand from the bobbin ground gear was flowing back and obscuring the lower panel. These fish now appeared to be more agitated and restless, using fast tail beat movements to keep station with the net. Many fish turned at right angles and struck out through the meshes; others, depending on their body girth size,

failed to escape and either were meshed (70mm mesh in this panel) or tumbled back down into the cod-end. The degree of agitation did not appear to relate to high density packing of individuals, which would have resulted in a more pronounced scattering and attempted escape through the meshes (Korotkow, 1969).

Only small groups of four or five fish passed this area at any one time, and it was concluded that a high percentage of the smaller whiting were lost in this part of the net. In the cod-end, whiting were seen pressed against the meshes exhausted and at no time seen to swim forwards with the net.

Cod, *Gadus morhua* L., size range 27—45cm

Cod were not as plentiful as haddock and whiting, occurring as isolated individuals and not in large aggregations. Insufficient information was available on whether this species would be herded by the sand clouds or bridles. Single cod were first seen swimming in the direction of tow very close to the bottom, intermingled with haddock and whiting in the column formation well ahead of the groundline. There was no evidence of over-exertion in their swimming behaviour at this point. These fish showed steady swimming movement. Eventually they began to tire and drop back close to the bottom, to a position near the bobbin groundline. At this position their steady swimming behaviour changed to a "kick and glide" action and then to a very pronounced fast zig-zag track between left and right quarters in front of the bosom bobbins. They swam very close to the bottom and often passed under and between other fish species. This zig-zagging of the cod was very noticeable even when large quantities of other species of fish were present in the mouth of the net. Individual cod eventually turned horizontally close to the sea bed and either swam into the net close to the belly netting panel or escaped under the bobbin spacers. The larger cod swam with the net for a duration of approximately 50—70 seconds, but the smaller ones dropped back into the net after 20—40 seconds. The bobbin spacers on the "Lossie Q" ground gear were approximately 16cm above the sea bed and the bobbin wheels were spaced at approximately 56cm intervals. A few individuals were seen to escape by turning out to the side over the rubber leg section of the lower bridle, at a position just ahead of where the wing line joins the bobbin rig. These fish were very close to the sea bed when their escape took place. No observations were obtained of cod in the funnel of the net. In the cod end, they were seen mixed with haddock and other species swimming forwards, but were frequently caught up in the swirling water movements.

Saithe, *Pollachius virens* (L.), size range 34—44cm

The saithe seen in these experiments were larger than the other species. The size range is based on those retrieved from the cod-end. No observation was made of the herding of saithe into the path of the gear by either the trawl bridles or sand clouds. On a few occasions, saithe were seen to react positively to isolated billows of sand cloud thrown up by the fishing gear. These individuals avoided the clouds by swimming upwards or sideways. Single fish and large shoals were observed on separate occasions for long periods at a towing speed of 1.5m s^{-1}, and at no time could their behaviour be regarded in any respect as panic stricken. During one experiment, a single saithe (approximately 40cm) swimming at 1.5m s^{-1}, 1m off the sea bed and approximately 2m ahead of the groundline, was observed for just over 6 minutes in the path of the net. This fish swam with ease, apparently unperturbed by the presence of the surrounding netting panels. At the termination of the observation period, the saithe was still swimming steadily forwards in the same position between the wings of the net. In another haul, a school of saithe (more than 100 individuals estimated as 35-50cm long)

held position in the mouth of the net (Plate VI), swimming just above the sea bed and extending upwards to approximately 2m (headline height – 4m). Fish on the lateral extremities of the school were as close as 50cm from the side netting and appeared to be keeping station with the meshes. The leaders of the shoal intermittently detached themselves from the front of the shoal, rose and then dropped back to take up a position at the rear. Other individuals dived to the sea bed and fed on sandeels in front of the bobbins. Stoma Stomach analysis from individuals taken from the cod-end confirmed the p presence of undigestedssandeels. When sandeels were falling back into the net in large numbers, saithe snapped at the sandeels as they passed or accelerated forward to feed on individuals from the sandeel shoal. This apparent feeding behaviour was seen on a number of occasions when towing at 1.5m s^{-1}.

Plate VI. School of saithe, *Pollachius virens* L., swimming in the mouth of the "Lossie Q" 4–panel trawl. Towing speed 1.5m s^{-1}.

When the speed increased to 1.8m s^{-1}, the school of saithe slowly fell back until all the fish were behind the bobbin groundline and inside the net. Close behind the bobbins, saithe rose and fell in an undulating swimming action.apparently affected by turbulence in this area. Large fronds of sea weed were entangled in the ground gear and it was obvious that the saithe were finding shelter in the eddies. When the towing speed was decreased again to 1.5m s^{-1}, the school slowly moved forward to the original position in front of the bobbins, again with the fish at the rear of the shoal swimming above the groundline and on the front belly panel of the net. At the

termination of this 16 minute observation period, with the school swimming steadily again between the wings of the trawl, the towing speed was increased in an attempt to catch them but only 30 saithe were recovered from the cod-end. However, standard practice when side trawling of coming around after completion of the haul may also account for the loss of most of these fish.

Flatfish, size range 16—36cm (measured from cod-end)

Flatfish, mostly plaice, *Pleuronectes platessa* L., dabs, *Limanda limanda* (L.), and a small number of lemon sole, *Microstomus kitt* (Walbaum), were common on these fishing grounds. Flatfish were herded into the centre of the ground-line bight by the herding effect of the bridles. The fish reacted and swam away at right angles when approached or touched by the bridles, which were moving obliquely over the sea bed at a small angle (11.5°, see Table I) to the towing direction. The fish, after being disturbed, moved away various distances (between ½m and 5m) before again being disturbed. This process was repeated again and again, the fish returning to points progressively nearer the mouth of the net, and in this zig-zag way individuals eventually arrived at the centre of the groundline (Fig. 5). Individual flatfish were observed from the time they arrived at the bobbins until they dropped back. They swam with the net for no more than 60 seconds at a towing speed of 1.5m s^{-1}, before dropping back into the net or under the bobbins. Of the flatfish measured at the end of each haul, plaice ranged from 19 to 36cm, dabs from 22 to 33cm and lemon sole from 29 to 34cm. No flatfish escaped once in the net; though some were seen swimming forward in the cod-end, most were pressed hard against the netting (Plate VII).

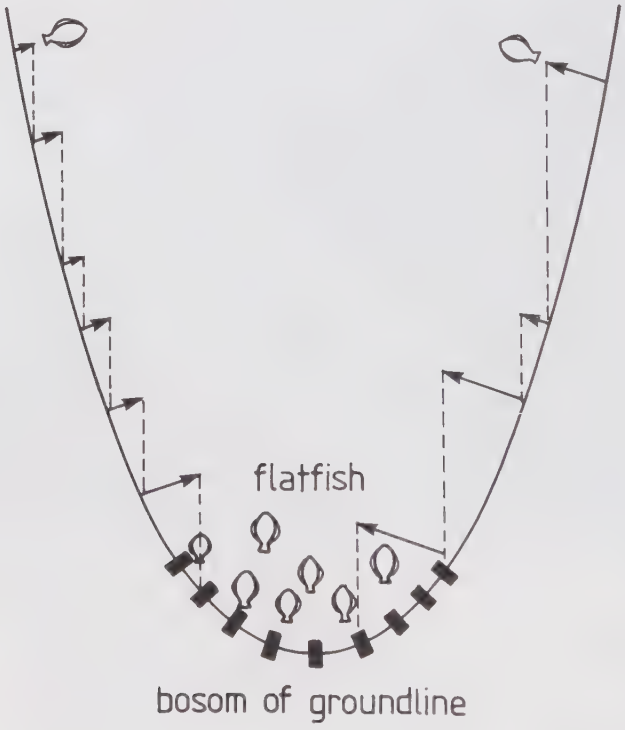


Figure 5. Direction of swimming of flatfish to effective herding by the sweeps and bridles.

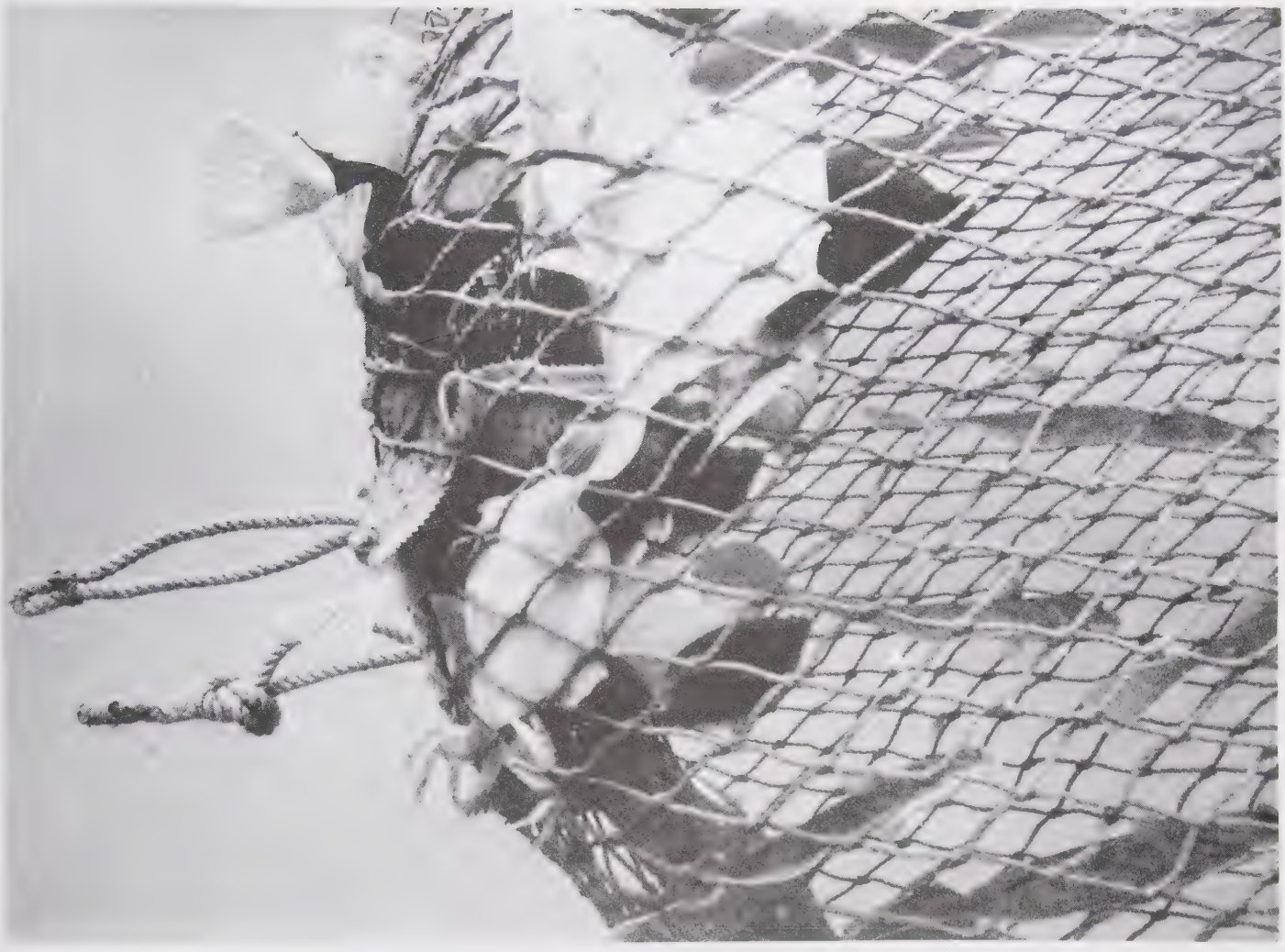


Plate VII. Side view of cod-end. Although most flatfish are seen pressed hard against the meshes, some are still swimming forward.

Grey gurnard, *Eutrigla gurnardus* (L.), size range 21–35cm (measured from cod-end)

Gurnards were plentiful on the grounds in both shallow and deep water. They were first seen swimming steadily in the direction of tow equidistant between the wings of the net, less than 1m off the bottom. They formed a narrow column a few fish wide and one to two fish deep, extending forward from the main mass of fish accumulated at the centre of the groundline bight, similar to the line formation of the haddock (Fig. 3). A few were herded into the centre of the gear by the bridles in a similar fashion to the flatfish. At a towing speed of 1.5m s^{-1} the larger gurnards (30 to 35cm) could swim with the gear for approximately 1½ minutes before tiring, but at a slightly slower speed of 1.2m s^{-1} (2½ knots) over 4 minutes could be achieved by the same size of fish. A number of fish dropped back into the net from a forward swimming position by turning quickly in the horizontal plane. Others appeared tired or uninterested and behaved in a similar way to the haddock, rising head up off the sea bed and dropping back 2 or 3m above the groundline into the net. A few gurnards were seen to escape both under the bobbin spacers and under the wing line. No fish was recorded escaping from inside the net or the cod-end.

Lesser-spotted dogfish, *Scyliorhinus caniculus* (L.), size range 50–75cm

Dogfish were abundant on the shallow part of the fishing grounds (20–30m) and were taken in large numbers on nearly every haul. The bridles disturbed them from their motionless state on the sea bed and herded them in towards the path of the gear. Some dogfish appeared sluggish when touched or stimulated by the lower bridle and swam only short distances before settling again. Eventually, owing to effective herding by the bridles, the fish accumulated in the centre of the groundline. This species swam with the tail slightly raised from horizontal, an action which was even more pronounced when the fish was stimulated to swim fast in front of the approaching bobbin rig. Plate VIII shows a dogfish in this position just before it passed back over the bobbin ground rig. Individual fish swam in front of the gear at 1.5m s^{-1} for less than 20 seconds before they fell back into the net. Most then swam briefly close to the belly of the net and were frequently seen tumbling back along the netting towards the cod-end. They did not swim in the cod-end, but but lay motionless, pressed against the netting.

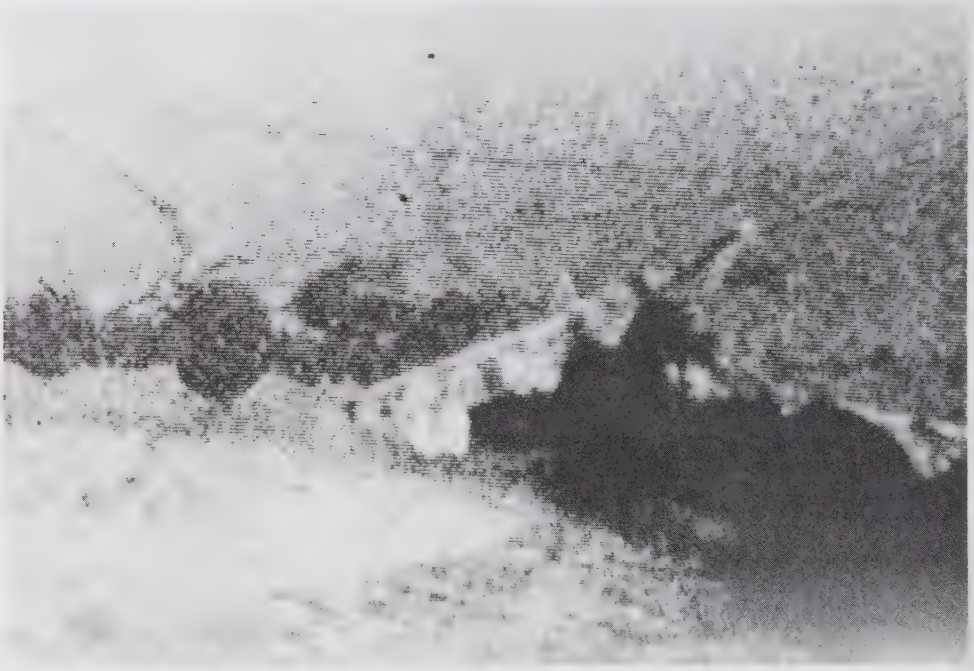


Plate VIII. A dogfish swimming with the tail slightly raised from the horizontal, just in front of the bobbin ground gear. (Still photograph from video)

Sandeels *(Ammodytidae)*, size estimate 10–20cm

Sandeels were abundant in the depth range 20–30m and were observed in nearly every haul. Owing to the large quantities and close packing of the sandeels within the school it was virtually impossible to describe the behaviour of individual fish. These results therefore describe the mass movements of the schools. Sandeel schools were seen at various heights in the path of the gear, being held in tight formation between the wings of the trawl. Some schools swam very close to the bottom, whereas on other occasions large densely packed schools filled the mouth of the net from sea bed to headline. At swimming speeds close to their maximum, sandeels used high tail beat frequencies in order to keep station with the gear at 1.5m s^{-1} (Wardle, 1976). Their endurance was never more than 15 seconds at 1.5m s^{-1}. Schools reacted and turned in mass formation, and although many passed back over the groundline most of these fish escaped. Large numbers escaped under the wing lines and over the headline (Plate IX) when dropping back, and then reformed and swam away. Some schools reformed and swam inside the net in a tightly packed formation and then suddenly

burst out through the panels of the netting, especially in the batings but never in the belly and seldom in the side panels. Sandeels which had escaped swam along with those inside the net, and on occasions individuals rejoined the group inside the net. Many sandeels escaped in the extension panel where it joins the cod-end, and only a few sandeels were ever recovered from the cod-end (mesh size 70mm).

Plate IX. Sandeels escaping over the headline of the trawl.

Mackerel, *Scomber scombrus* L.

Mackerel were seen during only one of the tows. This observation was of a group (approximately 50 fish, estimated 35–45cm long), swimming directly into the mouth of the net midway between headline and footrope. In the batings area of the net, where the diameter narrows to approximately 2m, the mackerel turned and swam forward again out of the net. Towing speed was 1.5m s^{-1}. Where the mackerel turned inside the net some individuals became meshed in the side and top panels. These fish were later measured and were between 37 and 41cm long.

Squid, *Loligo forbesi* Steenstrup, size 30–35cm

The most noticeable feature of the squid swimming in the path of the gear was the eyes, which were as striking as the vivid black spot on the flank of a haddock (Plate X). Squid were seen on only a few occasions in small groups of three or four individuals. They were first seen swimming in the path of the gear in the direction of tow, approximately 1 to 2m off the bottom.

They swam with the gear at 1.5m s^{-1} for no more than 30 seconds, before falling back, but from previous casual observations they are known to swim with fishing gears for longer periods. The same numbers were recovered from the cod-end at the end of the haul, so we may assume that few, if any, managed to escape from the net or the cod-end.

Plate X. Squid in the funnel of the net. (Still photographs from video)

Discussion

Value of the Direct Observation Technique

The results derived from the films and observations obtained during these experiments would not have been possible without the use of the divers' wet vehicle — TUV II. This vehicle, which is simple to operate and maintain, provides adequate shelter for the diving scientist at towing speeds up to 3m s^{-1} (6 knots) (Main and Sangster, 1978a). The diving scientist holding a TV camera has one obvious advantage over a remote camera system; he can pick out the more important points of interest from his wider field of view. The limitation of the TUV II system is primarily the relatively short time the divers have in which to make their observations. This problem can be overcome to a certain extent by using relay teams of specialist divers. Finding commercially important species of fish for observation in shallow water, 30–40cm, has proved a problem and the limited diving time can easily be used up in a vain search for fish. An element of good luck, being in the right place at the right time, accounts for some of the more spectacular films. The use of the TUV II, a suitable TV camera and well trained operators makes the most of these rare occasions.

Interpretation of the Echosounder Trace

In the echosounder trace in Plate II, the haddock and whiting marks showed that the shoals were approximately 4m high on the sea bed. However, those fish, when observed by the divers in the path of the gear, had settled into a line formation (Fig. 3) only 1m high on the sea bed. Some haddock were seen rising from the sea bed and becoming meshed in the square (height 4m); others were able to escape over the headline. Fishermen seeing haddock meshed in the square and echo traces similar to Plate II may suppose haddock to have remained at the 4m height all the way back to the net. This belief is not supported by our observations, which suggest that the haddock become meshed in the top of the net as a result of their natural rising behaviour.

Fish Formation and the Optomotor Response

The results from these experiments were obtained in daylight with good water clarity for United Kingdom waters, and we can expect that the behaviour of these fish in relation to the fishing gear was primarily governed by sight.

It was seen that haddock, whiting, cod, saithe and gurnard swam in formation equidistant from the wings, bridles and sand clouds, apparently keeping station with some visual fix on either side. The wing end spread was 8.5m and bridle spread approximately 14m at the front of the line formation (Table I). Plate XI suggests that although the selvedge, wing and headline ropes are visible, the actual meshes may not be visible to the fish. The visibility to the observer of different mesh sizes and colours of netting panels will change, however, depending on the water transmission, ambient light, visual range and the elevation of the fish eye to the object. Hemmings (1973) reported the herding of haddock, apparently due to the forward motion of the netting in the wings of a Danish seine-net, and concluded that this was an example of the optomotor response, a reaction fairly common in fish. It would suggest that, in our experiments, the fish in the line formation between the wings of the bottom trawl are able to see the wing line and selvedge ropes etc and are displaying a typical optomotor reaction. Dogfish did not show this response.

Plate XI. Looking into the mouth of the trawl from the port wing. The selvedge, wing and headline ropes are visible, but the actual meshes may not be visible to these fish.

Speed and Endurance

The swimming speeds and endurance of a fish are closely related to temperature and to its size (Wardle, 1977, 1981), and in the mouth of the net this speed will be dependent on the towing speed of the fishing gear (Wardle, 1976). Dogfish dropped back into the net after only 20 seconds and did not recover, yet mackerel swam into the net, turned and accelerated out again. If a stimulus, eg part of a trawl, causes a fish to keep station with it and swim until approaching tiredness or exhaustion, the fish either slows down and lets the stimulus pass or turns away from it. If it is in the mouth of the gear, the fish will either drop back into the approaching net or escape. Wardle (1976) described the thresholds of speed and endurance of some commercially important species of fish. The results from our experiments on the swimming endurance of the various species in the path of the net fall in line with these predictions. They show that the small fish became exhausted after only a short period of swimming at 1.5m s^{-1}, whereas larger fish are able to swim for long periods at their cruising speed. Once, however, saithe were seen to shelter by ducking behind the footrope bobbins to avoid the exhausting swimming when the gear was being towed fast.

Fish Escape

Once a fish is inside the net, it is most likely to be in a state approaching exhaustion, and so it will lose ground and fall back towards the cod-end, unless, like the mackerel, it has the energy resources to turn and swim out again. However, fish with small girth and some with a suitable behaviour reaction may be able to escape through the meshes of the net. Some haddock and sandeels, for example, escaped through the top panel of the net, and others of these same species escaped through the meshes in the cod-end. It seems likely therefore, that in bright conditions size of fish, mesh size and endurance of the fish are important if escape from inside the net is to take place.

In the rear part of the batings, where the funnel narrows, shoaling species will be made to swim closer and closer together. These fish will eventually reach a densely packed formation, resulting in the fish attempting to break out through the meshes (Korotkow and Martyschewski, 1977). In our experiments, only small numbers of individuals were present at any one time in this area, yet it was increasingly evident that many haddock and whiting succeeded in escaping in the batings. Did these fish feel over-crowded or threatened by the close proximity of the meshes, or did differences in water flow or changes in mesh size from one panel to another trigger this panic response?

Main and Sangster (1978a) described differences in the water flow in this area in front of the cod-end of a 4–panel trawl and more recently they found differences in this particular area both inside and outside the net in other bottom trawls. These differences in water flow depend on the mesh size, material and angle of inclination of the netting panels. Owing to incorrect rigging in the bottom trawl used in these experiments, two rows of 60mm meshes joining the 70mm panels of the batings gave an abrupt change in shape. It may also be important that these two rows were of black twine joining two panels of green netting. Possibly this change in the visual continuity of mesh size or colour of the netting caused the escape response. However, this would most probably stimulate the fish only under daylight conditions. We can say with a fair amount of certainty that once a fish is in the cod-end its chances of escape are limited. Escape will depend on the mesh size and girth of the fish. In our video observations young fish were seen wriggling out through the meshes (Plate XIIa and b) and others being forced out owing to water turbulence. Those fish that wriggled out swam away apparently unhurt, but the water surrounding the cod-end contained large quantities of suspended fish scales, particularly if sprats were present intthe net. We do not, at the moment, know whether these scales come

from young fish squeezing out or from those swirling inside the cod-end. However, casual observations have shown that scaling of fish also occurs well ahead of the cod-end. Escape will also depend on the shape and tension of the meshes.

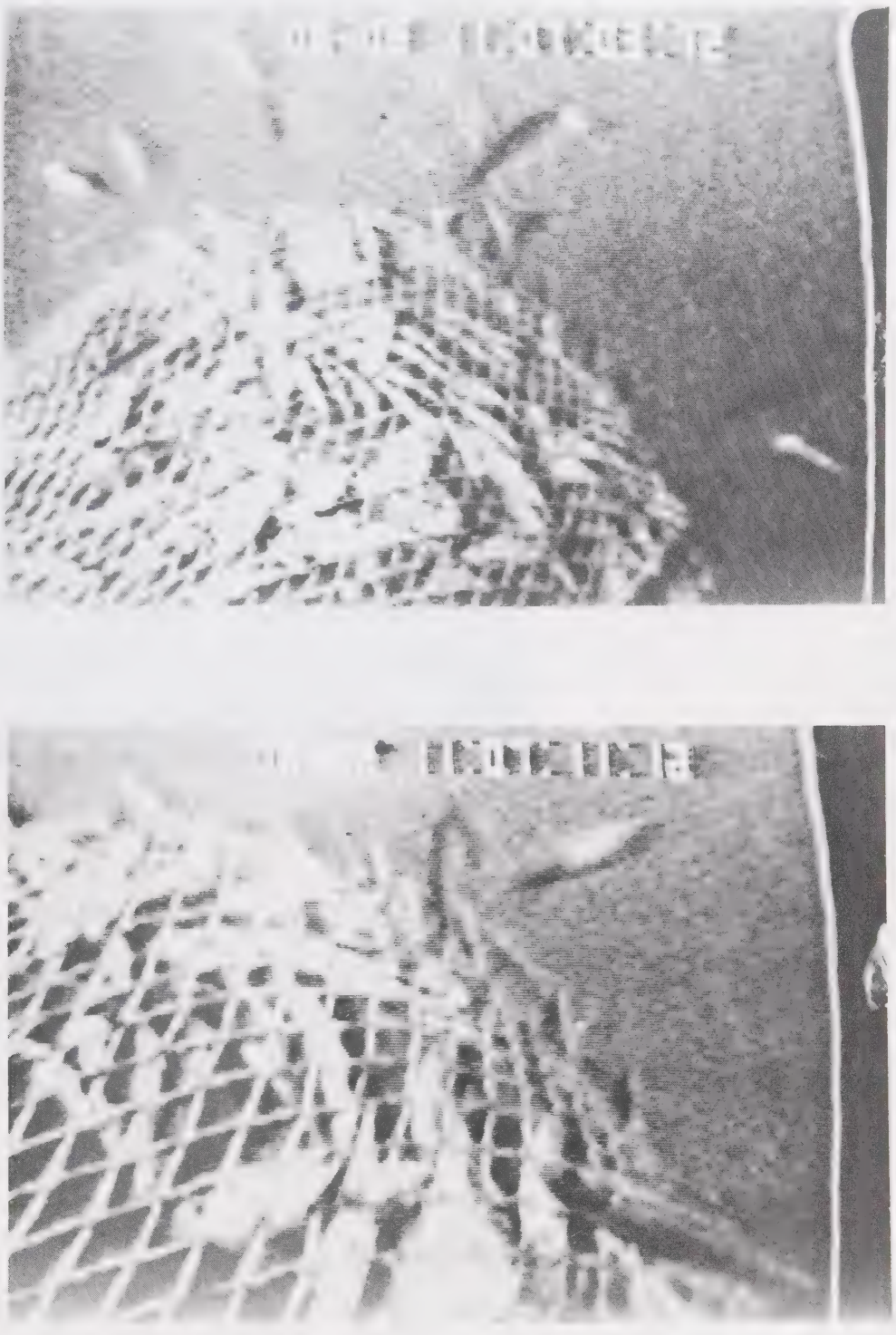


Plate XII. Small fish escaping through cod-end meshes. (Still photographs from video)

Bioluminescence

We know that fish can see, hear and swim and react in different ways to a fishing gear in bright conditions, but we know less about what happens in the dark, deep conditions where the ambient light is reduced. Blaxter and Parrish (1966) showed that cod, haddock and herring ceased to react to towed nets under darkened conditions, but to date really good evidence of non-reaction of fish to bottom trawls in darkness is still required. In darkness, bioluminescent dinoflagellates or ctenophores appear to make a moving object visible (Herring, 1978; Kelly and Tett, 1978). These

planktonic organisms tend to flash when disturbed by water movement and therefore a trawl moving through dark, deep water could be made wholly or partially visible if these organisms were present. Plate XIII shows a panel of netting which has been made visible owing to the presence of bioluminescence (Note – time of day 0120 hours). The netting in this experiment appeared more pronounced when the towing speed was increased but disappeared completely when the speed was reduced. The white streak across the lower half of the picture is an animal striking against the net, its trail being defined by bioluminescence.

Plate XIII. Panel of netting made visible due to bioluminescence. (Still photograph from video)

Future Developments

A possible application of the results of these experiments will be the development of more selective nets, allowing greater effective management of fish stocks. It is possible by using separating panels of netting to filter off various species of fish at three different heights when entering the net; cod, flatfish and skates at ground level, whiting with some haddock in the next level and haddock with some whiting in the top level (Fig. 6). Other experiments have also shown that fish and *Nephrops* can be separated by a single separating panel in the trawl.

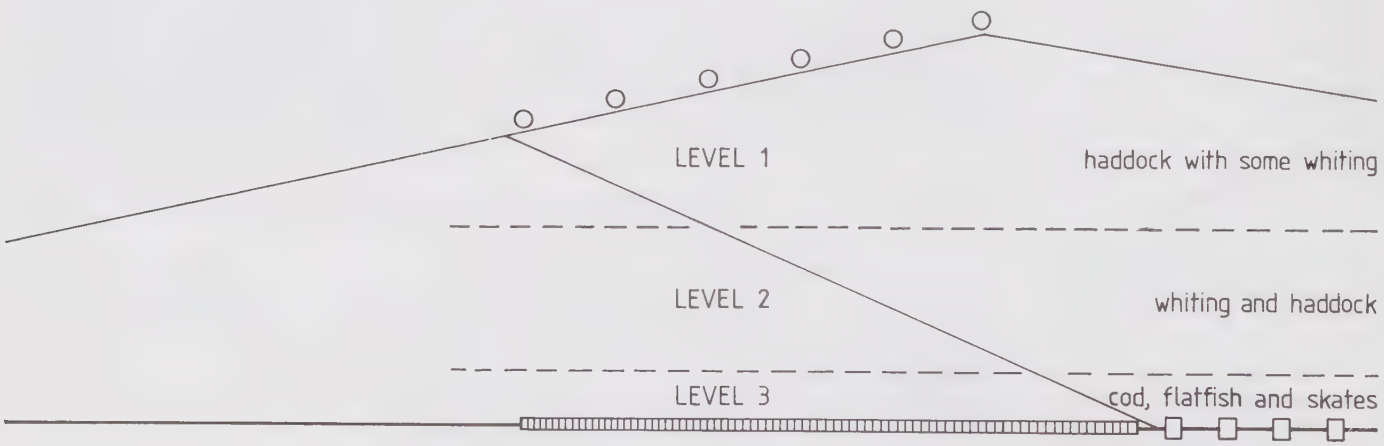


Figure 6. The principal of the species–selective trawl. Knowing the natural behaviour of the haddock, cod and whiting to a standard bottom trawl, it should be possible to separate the individual species into three levels during the catching process.

A further bonus to fishermen from the new nets would be that when the lower belly is torn out during a tow, fishing would continue in the upper levels. Normally a net ceases to fish when the belly is torn away. Preliminary trials with such experimental gears have given encouraging results, but further tailoring of the separating panels and direct observation of the reaction of fish to this type of net are required before qualitative conclusions are drawn.

Summary

Observations were made of the reactions of various species of fish to a "Lossie Q" 4–panel bottom trawl, which had a headline height of 4m, wing end height of 2.1m and wing end spread of 8.5m. This net, when towing in both directions over the edge of a 10^{o} slope, lifted off the sea bed at 1.5m s^{-1}. A number of commercially important roundfish species (haddock, whiting and cod) formed a narrow column or ribbon formation equidistant between the bridles and wings before crossing the bobbin ground gear.

The swimming endurance of most species is dependent on their length. Smaller fish dropped back into the net before the larger ones at a towing speed of 1.5m s^{-1}.

Cod showed a very pronounced, agitated, zig-zag swimming behaviour before turning low horizontally above the bobbins and back along the belly of the net.

Haddock rose consistently from the sea bed when tiring and turned into the mouth of the net. Some rose and escaped over a 4m headline at a towing speed of 1.5m s^{-1}.

Whiting, like cod, turned through 180^{o} horizontally back over the bobbins. These fish entered the net just higher than cod.

Saithe can swim in the mouth of a bottom trawl for more than 16 minutes at a towing speed of 1.5m s^{-1}. During this time, many dived to the sea bed and fed on sandeels. A number avoided fast swimming by sheltering in the eddies behind the bobbins.

At a towing speed of 1.5m s^{-1} mackerel swam head first into the trawl, turned and swam out again.

Small fish (haddock, whiting, sandeels) escaped through the meshes in the batings and cod-end.

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